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APPLICATION OF THE OECD EUTROPHICATION MODELING APPROACH TO ESTUARIES

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ABSTRACT: Approximately five years ago, the Organization for Economic Cooperation and Development (OECD) initiated a 22 country, 200 lake and impoundment study of nutrient load-eutrophication response relationships. Emphasis in the study is being given to the evaluation of the Vollenweider models for correlating nutrient load with eutrophication response. The U.S. part of this study included the investigation of about 40 waterbodies or parts thereof. The results of the U.S. and the other studies all show a strong correlation between the phosphorus load to a water body as normalized by mean depth and hydraulic residence time, and the planktonic algal chlorophyll, Secchi depth (water clarity), and the hypolimnetic oxygen depletion rate. These relationships have been developed to a sufficient degree of sophistication so that they are the method of choice for estimating the impact of altering the phosphorus load to a P-limited waterbody on eutrophication-related water quality.

While the U.S. OECD waterbodies were primarily lakes and impoundments, included as part of the data base upon which the statistical correlations were made were three parts of the Potomac estuary. It appears that in general, the OECD eutrophication modeling approach is applicable to estuarine systems as well as lakes and impoundments. In addition to reviewing the U.S. OECD study results, this paper presents a discussion of the modifications that may need to be made in the OECD-Vollenweider eutrophication modeling approach in order to apply it to some estuarine systems.

INTRODUCTION

With increasing emphasis being placed on management of excessive fertility-eutrophication within United States and other nations' tidal freshwater, estuarine, and marine waters, increased attention is being given to methods of formulating nutrient load-eutrophication response relationships for these waters. A prime example of this interest within the U.S. is the Chesapeake Bay Program, which is the focal point of this conference. Similar programs of this type need to be conducted for the New York Bight and other areas of the U.S. In the case of the New York Bight, in the summer of 1976 a massive area off the New York-New Jersey coast (8 by 100 miles - 13 by 160 km) of hypolimnetic waters became deoxygenated, which resulted in massive destruction of benthic fish and shellfish in this region (7, 15).

A similar type of problem of even greater magnitude occurred over the past several years in the Sato Inland Sea in Japan, where large populations of yellowtail and other fish have been killed because of excessive growths of toxic planktonic algae. Many of the prime coastal recreational areas of the world's waters, such as the Emilia Romagna Italian waters of the northwest Adriatic Sea and the coastal waters of the Costa del Sol (Spain) are showing significant water quality deterioration due to eutrophication which has or will soon adversely affect the use of and recreation-based revenue from these regions.

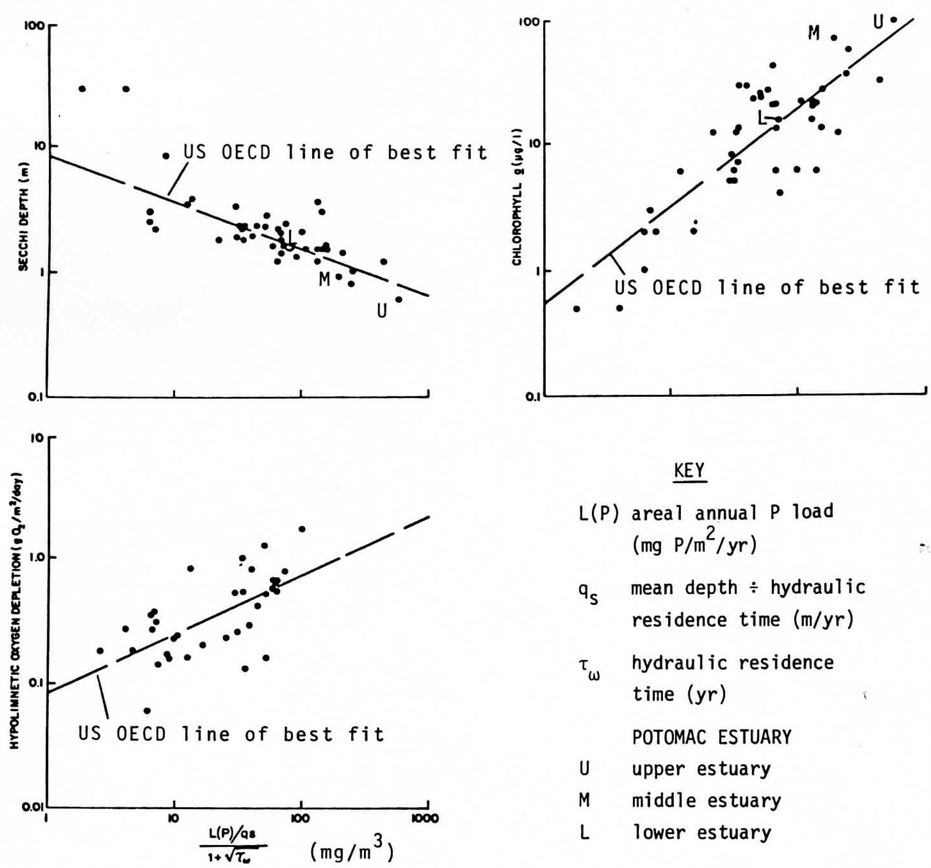
The OECD eutrophication modeling approach has been found to be a useful tool to predict changes in eutrophication-related water quality that will result from altering the phosphorus load to a waterbody by a given degree. This paper discusses the applicability of these results to nutrient load-eutrophication response modeling for estuarine, tidal freshwater, and marine systems.

CHARACTERISTICS OF THE OECD EUTROPHICATION STUDY PROGRAM

The Organization for Economic Cooperation and Development Eutrophication Study Program was initiated approximately half-a-dozen years ago to develop nutrient load-waterbody response relationships that could be used for management of water quality in excessively fertile waterbodies. It included detailed nutrient load-eutrophication response studies on approximately 200 waterbodies located in 22 OECD member nations in Western Europe, Japan, Australia, and North America. Within the U.S., approximately 40 waterbodies or parts thereof were included within this program, including the Potomac estuary. Two reports have been generated within the U.S. covering these studies. One (21) consisted of a series of individual waterbody reports in which the investigator who had conducted intensive studies of that waterbody prepared a review of these studies and provided data in a standardized form on the characteristics of the waterbody needed to make a load-response assessment. An overall summary report was prepared by Rast and Lee (16) in which the standardized data from each of the individual studies were examined collectively to determine what trends and in particular what nutrient load-eutrophication response relationships could be generated from these data. Lee et al. (12, 13) prepared summary papers discussing the results of the U.S. OECD eutrophication study.

The principal output from the Rast and Lee report are three relationships which are shown in Figure 1. The abscissa in this figure is the areal phosphorus load to the waterbody normalized by the waterbody's mean depth and hydraulic residence time. Vollenweider (24) proposed that this normalization factor would be suitable for use in relating phosphorus load to eutrophication response as measured by planktonic algal chlorophyll. Rast and Lee have shown that his proposals were appropriate and that there is a remarkably good correlation between the normalized phosphorus load and the planktonic algal chlorophyll for approximately 40 U.S. waterbodies. They extended Vollenweider's concept to include the Secchi depth (water clarity) and hypolimnetic

FIGURE 1. U.S. OECD data applied to P load – summer mean chlorophyll, summer mean Secchi depth, and hypolimnetic oxygen depletion rate relationships.



oxygen depletion rate (Figure 1). It should be noted that while the overall OECD eutrophication study results have not yet been published, they will be released in the near future. These results have been compared to the Rast and Lee relationships developed based on the U.S. OECD eutrophication study data base, and it has been found that waterbodies located throughout Western Europe, North America, Japan, and Australia fit these relationships well. As discussed by Vollenweider (25) the normalized P load to a waterbody can also be correlated to the primary productivity in the waterbody.

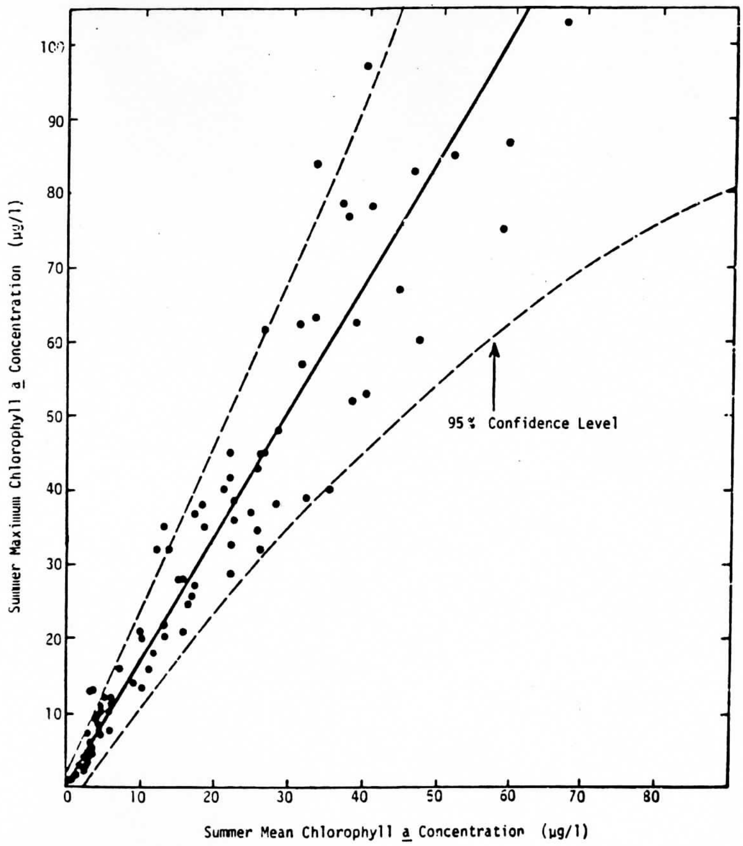
Since the completion of the Rast and Lee report in the summer of 1977, Lee and his associates have continued to study nutrient load-eutrophication response relationships for a variety of waterbodies in the U.S. and abroad. They have found that the additional 100 or so waterbodies they have studies obey the same load-response relationships that were developed based on the 40 U.S. OECD waterbodies, so that at this time the relationships depicted in Figure 1 have been found to appropriately represent approximately 300 waterbodies. It is now clear that Vollenweider's original concept of relating a normalized phosphorus load to eutrophication-related water quality has general applicability to many waterbodies located throughout the world. In fact, if waterbodies do not fit these relationships, there is a very good indication that either the data which were used as a basis for judging the appropriateness of fit were incorrect or there is something peculiar about the way in which the waterbody utilizes its phosphorus load in developing planktonic algae.

While the relationships shown in Figure 1 for chlorophyll and Secchi depth are based on mean concentrations generally through the summer months, Jones et al. (5) have shown that the mean values for this period can be readily translated into single maximum values. Figure 2 presents the relationship between mean and maximum planktonic algal chlorophyll concentration based on about 90 waterbodies or parts thereof located in various parts of the world. It is evident that below about 50 μg/l chlorophyll which would be generally classified as the lower end of the hypereutrophic range, there is a remarkably simple relationship between mean and maximum chlorophyll concentrations. The same approach can be extrapolated to the water clarity as measured by Secchi depth through the relationships shown in Figure 1.

Recently, Lee and Jones (9) have extended the OECD eutrophication modeling approach to relate normalized phosphorus load to fish yield for a wide variety of waterbodies in various parts of the world. This relationship is shown in Figure 3. It is evident from this figure that phosphorus load as normalized based on the Vollenweider concept is a tremendously powerful predictor of the overall functioning of aquatic ecosystems in producing phytoplankton.

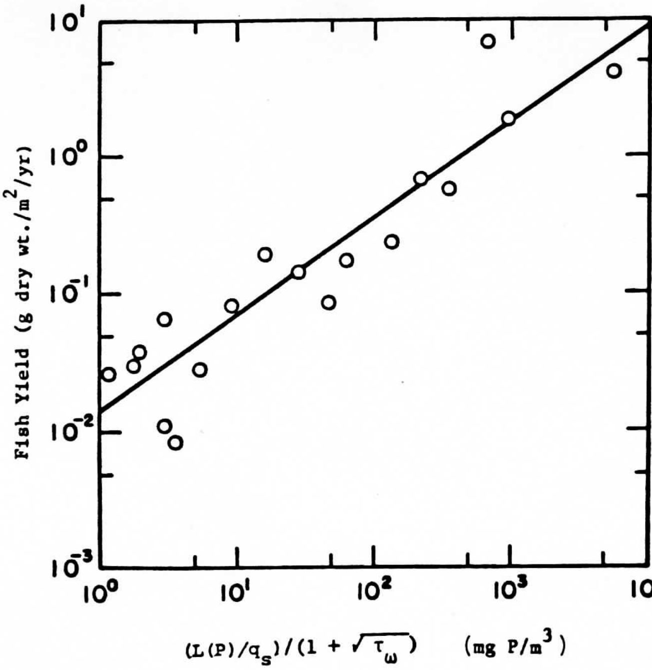
The fact that over 300 waterbodies fit the U.S. OECD load-response relationships imparts considerable credibility to this modeling approach. However, in order to determine the ability of this modeling approach to track changes in water quality with changes in P load, Rast et al. (17) have

FIGURE 2. Relationship between mean and maximum planktonic algal chlorophyll concentration for 90 waterbodies.



examined "before and after" data for 9 waterbodies which have had changes in their phosphorus loads and for which there were data on the water quality characteristics before and after these changes occurred. The results of this study follow the predictions made by Rast and Lee (16) as to how waterbodies would respond to changes in water quality as a function of changes in phosphorus load. In general, Rast et al. found for a variety of waterbodies located throughout the world that when the P loading term (P load normalized by mean depth and hydraulic residence time) is altered as with a P load reduction, the load-response relationship for that waterbody tracks down parallel to the U.S. OECD eutrophication study lines of best fit shown in Figure 1. It appears that whatever caused a waterbody's load-response relationship to deviate from the U.S. OECD line of best fit was a constant factor in both the "before" and "after" phosphorus loads for the waterbody.

FIGURE 3. Relationship between P load and fish yield. Line of best fit: Log Fish yield = 0.7 log $\{L(P)/q_s)/(1+\sqrt{\tau_\omega})\}$ -1.86. (r^2=0.86)



APPLICATION OF OECD EUTROPHICATION STUDY RESULTS TO MANAGEMENT OF EUTROPHICATION-RELATED WATER QUALITY IN ESTUARIES

While the primary focal point of the OECD eutrophication study program is freshwater lakes and impoundments, the U.S. part of this program included three sections of the Potomac estuary. Jaworski (2) has summarized the U.S. EPA studies on the Potomac estuary. He presented a review of these studies at this symposium. Rast and Lee (16) have shown that the data for each part of the Potomac estuary, marked on Figure 1, fall in the same family of points in the U.S. OECD eutrophication studies as freshwater lakes and impoundments.

Table 1 presents various characteristics of the three reaches of the Potomac estuary shown in Figure 4 as determined by Jaworski (2) and reported in Rast and Lee (16). The typical ranges of chlorophyll concentrations and Secchi depth found in sections of each are presented as "measured" levels; those predicted based on the U.S. OECD lines of best fit shown in Figure 1 are presented as "compouted" levels. The computed chlorophyll levels are, for all three reaches, within the range of values typically found; for the upper and lower reaches, the computed value is approximately equal to the average of the high and low measured values. When the computed mean concentration values are converted to maximum values using the relationship shown in Figure 2, maximum

TABLE 1. Characteristics of the Potomac Estuary[1]

Parameter	Reach of Potomac Estuary[2]		
	Upper	Middle	Lower
Mean depth (m)	4.8	5.1	7.2
Hydraulic residence time (yr)	0.04	0.18	0.85
Areal P loading ($gP/m^2/yr$)	85	8	1.2
Mean chlorophyll (μg/l)			
measured	30-150	30-100	10-20
computed[3]	80	31	13
Maximum chlorophyll -			
computed (μg/l)	136	53	22
Mean Secchi depth (m)			
measured	0.4-0.8	0.5-1.3	1.0-2.3
computed[3]	0.8	1.3	1.6

[1]After Jaworski[2] - Rast and Lee[16].

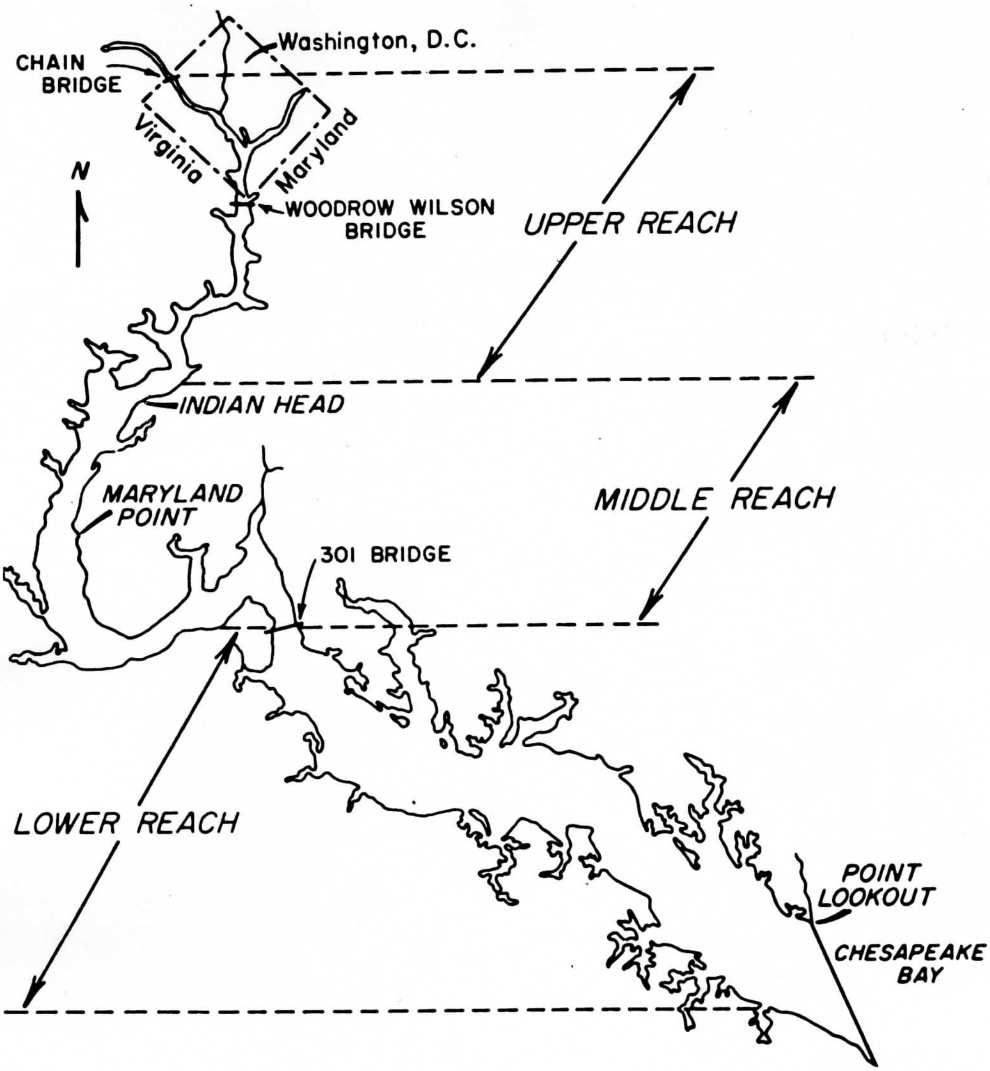
[2]See Figure 4.

[3]Using US OECD line of best fit.

chlorophyll levels on the order to the high end of the measured range are found. Also as seen in Table 1, the U.S. OECD load-response relationship provided a good approximation of the Secchi depth values on all three reaches of the Potomac estuary.

While at first glance it may seem to be somewhat extraordinary that lakes and estuaries behave in the same manner with respect to algal use of phosphorus, actually when one examines the nature of the OECD eutrophication modeling, approach, it is evident that this approach is based on the fact that a certain amount of phosphorus is needed in a waterbody to produce a certain crop of phytoplankton. It is important to emphasize that the OECD eutrophication modeling approach is currently limited in its applicability to phosphorus-limited systems where the peak of the phytoplankton biomass is governed by the amount of available phosphorus present in the water column. The Vollenweider approach is simply employing what are sometimes called the "Redfield numbers," which indicate that phytoplankton are composed of approximately 106 carbon atoms for every 16 nitrogen and every one phosphorus atom and that algae take up these three elements in roughly that proportion. While individual species of algae show differences in the C:N:P stoichiometry, freshwater, estuarine, and marine algae all have on the order of the same ratios. It makes little difference whether the phytoplankton are marine or freshwater. They have essentially the same composition and nutrient requirements.

FIGURE 4. Potomac estuary.



One of the most significant questions about the application of the OECD eutrophication modeling approach to estuaries is: What is an appropriate mean depth and hydraulic residence time for the estuarine system? Jaworski, in developing the data for the Potomac estuary, has assumed a simple plug flow model based on water displacement. While this approach worked well for the Potomac estuary, there may be situations, especially where there is a well developed salt wedge, where the plug flow assumption is not applicable or where the approach needs to be modified to consider mixing between surface freshwater and bottom salt water. Also, the appropriate mean depth to use may not be the morphological mean depth, but rather the depth of the surface freshwater layer. Lee and Jones (6) suggested that this modification in mean depth may be necessary for applying the OECD eutrophication modeling approach to the Emilia Romagna Italian coastal waters of the Adriatic Sea.

Another factor that can influence the applicability of the U.S. OECD eutrophication modeling approach to estuarine systems is the fact that many estuaries have sufficient amounts of inorganic and organic turbidity to limit phytoplankton growth. This is especially true along the south Atlantic and the northern Florida through Texas Gulf Coast. In these systems, the non-phytoplankton related turbidity may prevent the biomass from developing to its maximum potential based on the nutrient concentration of the water. Under these conditions, the chlorophyll that is observed during the summer growing season would average somewhat less than that predicted based on the OECD eutrophication modeling results because of the fact that the phytoplankton growth is more severely light-limited than it would be if the turbidity were due only to phytoplankton.

The first step in establishing appropriate phosphorus loads to a waterbody is to be certain that phosphorus does limit or can be made to limit maximum phytoplankton production during the time of year of water quality concern. This type of determination can best be made by examining the soluble orthophosphate, nitrate, and ammonia concentrations during the period of water quality concern. If phosphorus is limiting peak algal biomass production, then the available P concentration found during peak biomass will be on the order of a few μgP/l. Similarly for nitrogen to be limiting, the sum of the concentrations of nitrite, nitrate, and ammonia will be on the order 15 to 50 μgN/l during this period. If neither available N nor P is reduced to these levels during the period of maximum biomass, then the concentrations of N and/or P are not likely significantly limiting algal growth. Light is generally always a limiting factor in governing phytoplankton development within a waterbody, but given sufficient time, the importance of nutrients as a limiting factor may become dominant for any particular light conditions. It is this condition that is of importance in managing eutrophication-related water quality.

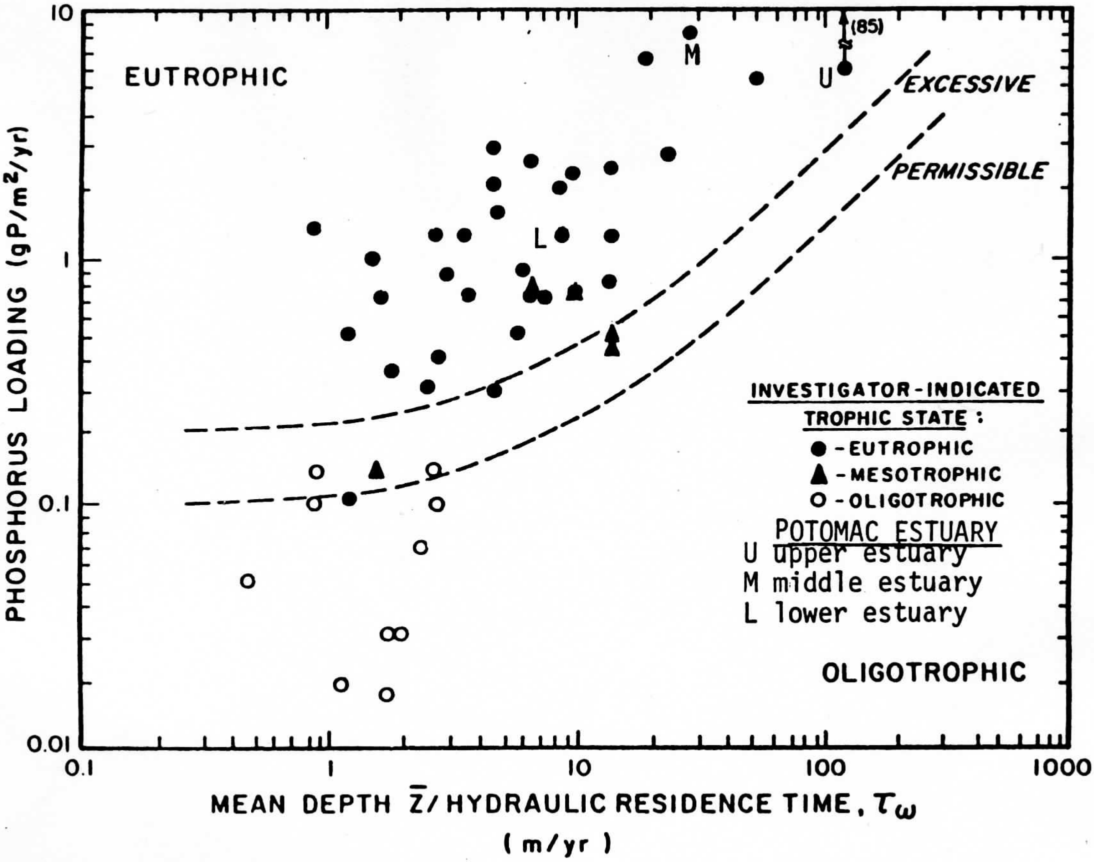
In many marine waters, phytoplankton growth is limited by nitrogen rather than phosphorus. Therefore, there may be a small region in the upper part of the estuary where phytoplankton growth is phosphorus limited during the summer period but as the marine waters are mixed with fresh water, the system should shift over to nitrogen limitation. Since many estuarine systems have nearby population centers and large amounts of domestic wastewaters are discharged into the estuary near the head end, and since the nitrogen to phosphorus ratio in domestic wastewaters is strongly in favor of nitrogen limitation for phytoplankton growth, it is conceivable that some estuaries will have few areas where phosphorus is the element limiting maximum phytoplankton biomass production. If the situation occurs that the estuary of concern is not P limited, then the OECD eutrophication modeling approach will not, without modification, accurately predict biomass as measured by chlorophyll, since these relationships were derived primarily based on waterbodies in which maximum biomass production was limited by phosphorus content of the water. When nitrogen limits peak algal biomass, the relationship between algal biomass and P concentration or load is on the plateau of a plot of algal biomass as a function of P load (or concentration); additional P input does not result in additional algal biomass. In order to apply the Vollenweider-OECD eutrophication modeling approach, a determination must be made of how much P load reduction must take place to cause phosphorus to limit algal biomass production. When that P load is reached, then further reductions in P load will result in decreased algal growth, i.e., the biomass-P concentration relationship is on the steep portion of the plot. In order to make this assessment, the mean available nitrogen concentration during the growing season of water quality concern must be divided by 7.5 to determine the mean P concentration necessary to attain the "optimum" algal stoichiometric ratio of 16:1 N:P atomic ratio discussed previously. At P concentrations below this level, P becomes the potentially limiting element. The P load corresponding to the calculated P concentration can be estimated through the use of the $(L(P)/q_s)/(1 + \tau_\omega)$ term (where L(P) is the areal annual P load, and q_s is the mean depth ÷ hydraulic residence time (τ_ω)) since it is equivalent to the average P concentration in the waterbody.

It is important that all determinations of limiting nutrients be conducted during the period of water quality concern. Algal bioassays such as those developed by the U.S. EPA (27, 28) for determining limiting nutrients should be performed on water samples collected during the period of concern. It has been found that N:P ratios measured and algal bioassays conducted at other times of the year may yield unreliable estimates of limiting nutrients during the critical water quality period. This is a result of the fact that the N:P ratio is a function of the relative rates of supply of available N and P from external as well as internal sources.

In the freshwater part of the estuary, there is potential for blue-green algal development, some of which are nitrogen fixers at times. Under these conditions, of course, the nitrogen load would have to be adjusted for nitrogen fixation since much higher biomasses are possible when nitrogen fixation is progressing at a rapid rate. This does not appear to be a significant problem in the marine part of the estuary where the nitrogen-fixing blue-greens do not seem to be predominant.

The OECD eutrophication modeling approach is patterned from the developments of Vollenweider (22, 23) in which he attempted to relate phosphorus load to a mean depth/hydraulic residence time quotient where, as shown in Figure 5, two curved lines represent "excessive" and "permissible" loading lines. It is important to emphasize, as pointed out by Jaworski (2), that this approach may not be valid for some estuarine systems. As discussed by Rast and Lee (16), the original concept of

FIGURE 5. U.S. OECD data applied to modified Vollenweider P loading-mean depth/hydraulic residence time relationship.



excessive and permissible loadings by Vollenweider was based on the work of Sawyer (20) who correlated nitrogen and phosphorus concentrations in 22 southern Wisconsin waterbodies with his subjective assessment of water quality in these waterbodies in terms of their recreational use. It is important that the concept of excessive and permissible nutrient loads be established on a case-by-case evaluation since what might be deemed "excessive" in tropical waters might be satisfactory in many other estuarine waters. It is far better to work out an approach whereby a certain phytoplankton chlorophyll concentration is established as a desirable goal and then the appropriate corresponding phosphorus load needed to attain this goal is determined based on the waterbody's mean depth and hydraulic residence time. The greeness of a waterbody is an important parameter by which water quality is assessed. The public's perception of greenness varies widely, depending primarily on the background turbidity in the system. At low levels of organic color and detritus and inorganic materials suspended in the water column, a relatively small increase in phytoplankton chlorophyll is readily discernible and objectionable to many individuals. In more turbid systems, however, the chlorophyll content can increase significantly and still not significantly alter a beneficial use of the water. It is important to set water quality objectives based on impairment of beneficial use and not some arbitrarily established phytoplankton chlorophyll value. For some estuarine systems as well as nearshore marine waters, the factor governing the acceptable level of chlorophyll - P load may be the hypolimnetic oxygen depletion which would in some years tend to destroy the benthic fish and shellfish below the thermocline-chemocline in the area, such as occurred in 1976 off the coast of New Jersey.

Another effect of excessive fertilization of estuarine and marine waters which may alter the positions of the "excessive" and "permissible" loading lines is the one mentioned previously that occurred in the Sato Inland Sea in Japan, where toxic dinoflagellate blooms killed millions of yellowtail fish that were being cultured for commercial purposes. If this were the beneficial use of a water, the nitrogen and/or phosphorus load to that region would have to be correlated to the chlorophyll content of the particular dinoflagellate which would be toxic to fish. These numbers may be markedly different than what is typically found to interfere with recreational use of the waterbody.

APPLICATION TO WATER QUALITY MANAGEMENT FOR THE POTOMAC ESTUARY

Jaworski (2) utilized some of the initial relationships developed by Vollenweider as a means of establishing the phosphorus loads that should be obtained in order to achieve a certain water quality in various parts of the Potomac estuary. Since Jaworski's efforts along this line, the OECD Eutrophication Study Program has been completed with the result that a much larger data base is now available for establishing lines of best fit between load and response for various types of waterbodies. This section of this paper uses the data obtained by Jaworski to determine the eutrophication-related water quality that will result from altering the P load to the upper Potomac estuary.

Jaworski (2) reported that phytoplankton biomass production in the upper and middle portions of the Potomac estuary becomes nitrogen limited in the summer months. Examination of Jaworski's data (4) on N and P concentrations shows that N limitation during the summers when the data used herein were collected, is unlikely. If a nutrient is limiting, it is more likely to be P. With a small P load reduction, the phytoplankton growth in the upper Potomac would become P limited; therefore the OECD eutrophication modeling approach should be applicable to predicting the planktonic algal chlorophyll that will develop from a certain P load reduction to the upper Potomac estuary.

Jaworski (2) estimated that in 1970, 10,900 kg/day of phosphorus were added to the upper reach of the Potomac estuary from domestic wastewater sources. Since phosphorus in domestic wastewaters can be readily reduced by about 90 percent by chemical precipitation with iron or aluminum salts during normal secondary wastewater treatment for a cost of less than a quarter of a cent per person per day, the phosphorus load from direct discharge of wastewater treatment plant effluent to the upper estuary could therefore be readily reduced to approximately 1,000 kg/day. Using the relationships developed in the U.S. OECD eutrophication study, achieving this load (assuming that 50 percent of the upper Potomac basin load would also be removed as a result of wastewater P removal (2)) would result, under low flow conditions of 40 m^3/sec, in an average summer planktonic algal chlorophyll of about 45 µg/l, and under median flow of 185 m^3/sec, about 23 µg/l. Jones et al. (5) developed a statistical correlation which showed that the maximum summer planktonic algal chlorophyll concentration is about 1.7 times the summer mean. Therefore, summer maxima would be predicted to be on the orders of 77 and 39 µg/l (for low and median flows, respectively) for the upper parts of the Potomac estuary if 90 percent P removal took place in the basin. Jaworski (2) reported that a 1,000 kg P/day domestic wastewater treatment plant P load (with an assumed 50 percent reduction in upper basin P load) would result in a 25 µg/l chlorophyll concentration in the upper estuary. This was estimated using a dynamic modeling approach and agrees with what is predicted based on the OECD modeling approach. A 25 µg/l mean chlorophyll concentration does not, however, generally represent good water quality for most recreational purposes. Such a water would experience excursions of chlorophyll concentration about 40 µg/l during the summer, according to the relationship developed by Jones et al. (5). It is evident that much smaller loads will have to be attained in order to achieve a generally acceptable eutrophication-related water quality in the upper parts of the Potomac estuary.

Jaworski (2) indicated using another approach, that it would be necessary for the nutrient loads to be reduced to 1913-1920 conditions (about 600 kg P/day) to have no major aquatic plant nuisances (in the upper estuary?). Using the U.S. OECD eutrophication model, this load would result in mean chlorophyll concentrations in the upper estuary of 8.3 and 25 µg/l during median and low flows, respectively. While achieving this level would significantly improve the eutrophication-related water quality, it would not reduce aquatic plant nuisances in this area to levels which are generally considered acceptable for recreational uses. It should be noted that according to Jaworski (Personal Communication, 1980), substantial P load reductions have been attained at the wastewater treatment plants in the upper estuary watershed and a noticeable improvement in eutrophication-related water quality has resulted.

It is possible through advanced wastewater treatment processes to reduce the phosphorus content of domestic wastewaters to a few tenths of a mg/l P. This would represent a significant increase in cost over the 1 mg/l effluent phosphorus that is readily achievable by iron or aluminum hydrous oxide coprecipitation. There are also some questions about the potential benefits of the removal of phosphorus to this extent from domestic wastewaters because of the fact that the additional costs are largely associated with removal of particulate forms of organic and inorganic phosphorus, some of which may not be available to support phytoplankton growth in the receiving waters. Lee et al. (11) have recently completed a comprehensive review on the current state of knowledge on the measurement and environmental significance of various forms of phosphorus that are important in developing a phosphorus management strategy for a waterbody. They pointed out that before any large scale significantly improved sedimentation or filtration is initiated on domestic wastewaters for phosphorus control, studies should be conducted to determine how much of the phosphorus that will be removed by increased particle removal in the treatment plant, would be available to support phytoplankton growth in the receiving waters. These studies must be done using algal bioassays. As discussed by Lee et al. (11), at this time there are no reliable chemical procedures to determine whether phosphorus in a wastewater sample is available to support algal growth in receiving waters. The chlorophyll concentration that would be expected to result from achieving a 0.1 mg P/l effluent concentration would be about 25 µg/l provided that the additional P removed below the 1 mg P/l effluent level was largely available to support algal growth. A 25 µg/l average summer chlorophyll would generally cause the water quality to be considered somewhat degraded.

It is important to note that the various loadings that have been used in developing these chlorophyll estimates are based on Jaworski's early 1970 work. While the average and maximum chlorophyll concentration predicted by the OECD eutrophication model for the P loads would be applicable to the situation today, the phosphorus loads that could be achieved by reducing phosphorus in domestic wastewaters by various amounts has changed since 1970, due to increased population in the Potomac estuary area and voluntary reduction of the P content in household laundry detergent formulations. A comparison should be made between current phosphorus loadings to the upper Potomac from domestic wastewater treatment plants achieving various degrees of phosphorus removal and those used in these computations. If there are significant differences, then adjustments should be made in these values to correct for these differences.

One of the proposed solutions for minimizing eutrophication in the Potomac estuary area is the passage of a detergent phosphate limitation. At the time that Jaworski conducted his studies of the phosphorus content of domestic wastewaters across the U.S., approximately 50 percent of the P in domestic wastewaters was derived from phosphorus use as a builder in household laundry detergents. Today this value has been voluntarily decreased in all parts of the U.S. to about 25 percent, which means that the benefit of improved water quality arising from the removal of phosphorus from detergents is much smaller today than it was ten years ago. In the case of the upper reaches of the Potomac estuary, a detergent P ban would not drop the P concentrations sufficiently to have a discernible effect on water quality.

APPLICATION OF OECD MODELING TO UPPER CHESAPEAKE BAY

Jaworski (3) has provided sufficient information on the upper Chesapeake Bay to enable application of the OECD eutrophication modeling approach to this waterbody. For the main part of the Bay, Jaworski estimated for the period 1969-1971 a mean depth of 6.5 m, average hydraulic residence time of 1.2 years, and a P load of 1.3 $g/m^2/yr$. Using these values and the U.S. OECD eutrophication study line of best fit relating normalized P load to chlorophyll, a summer average planktonic algal chlorophyll concentration of 26 μg/l is predicted. This estimate is in agreement with the data reported by Salas and Thomann (19) of approximately 20 to 30 μg/l average chlorophyll for the summer of 1965. This close match provides additional verification of the applicability of the OECD modeling approach to estuarine systems.

Jaworski (3) estimated that approximately 70 percent of the P load to the upper part of the Chesapeake Bay is from domestic wastewater sources. Since approximately 90 percent of the P in domestic wastewaters can be readily removed using chemical precipitation techniques in normal secondary wastewater treatment, it is of interest to estimate the potential water quality benefits that could be derived from initiating this removal in the upper Chesapeake Bay watershed. Attainment of a 0.5 $gP/m^2/yr$ load will result in a mean summer chlorophyll concentration of 11 μg/l. This P loading can be achieved through initiating P removal at the domestic wastewater treatment plants in the upper Chesapeake Bay basin at a cost to the residents of less than a half a cent per person per day. Following this approach would result in a significant increase in the overall eutrophication-related water quality in the upper Chesapeake Bay. This part of the Bay could be changed from hypereutrophic to the transition area between mesotrophic and eutrophic based on the results of the OECD eutrophication study program. As with the upper Potomac, passage of a detergent P limitation would not significantly change the water quality of the upper Chesapeake Bay.

COMPARISON OF OECD AND DYNAMIC MODELING APPROACHES FOR EUTROPHICATION-RELATED WATER QUALITY MANAGEMENT

Two basic approaches have developed for estimating the benefits in eutrophication-related water quality that can accrue from controlling phosphorus inputs to a waterbody by a certain amount. One of these, the dynamic modeling approach, formulates the various processes that govern the transformation of phosphorus, nitrogen, carbon, sunlight, and other inputs into phytoplankton biomass, into a series of differential equations which, when solved simultaneously for a certain phosphorus load, provide an estimate of the planktonic algal biomass that will be present in a waterbody. The other approach is that originally developed by Vollenweider in which a relatively simple correlation is established between a normalized phosphorus load and the planktonic algal chlorophyll. It is important to note that while the dynamic modeling approach can be simplified to express the same general relationships as the OECD eutrophication modeling approach, this does not mean that they are both equally valid as management tools. There are very significant differences in the validity of these approaches in predicting P load-eutrophication response relationships for waterbodies. The dynamic modeling approach in general does not cover all of the physical, chemical, and biological processes that occur in waterbodies adequately to be system independent. Therefore, dynamic models must be tuned to each particular system. This tuning process is by far the greatest deficiency of these models and frequently limits their applicability for predicting planktonic algal chlorophyll under significantly altered phosphorus loading conditions. As discussed by O'Connor at this symposium, attempts have been made to use the dynamic modeling approach on a number of estuaries. It has failed to properly predict the biomass that developed in the system after conditions were altered. This failure would be expected of any dynamic model that must be tuned to each particular system. These system-dependent models should not be used for management purposes until this deficiency has been corrected.

An example of the lack of appropriate predictability of dynamic models for management of water quality in the Great Lakes was a model developed for prediction of hypolimnetic oxygen depletion in Lake Erie. A task group of the U.S.-Canadian Great Lakes Water Quality Agreement drafting committee, using a dynamic model, predicted that oxygen could be maintained in the hypolimnion of Lake Erie with a P load to this lake of 11,000 mt/yr. Lee and Jones (8) and Lee et al. (14) using the OECD eutrophication modeling approach, Vollenweider (26) using an independent modeling appraoch, and Chapra (1) have shown that this number is far in excess of the P load that can be allowed and still maintain oxygen in the hypolimnion of this lake under all conditions. According to the calculations of Vollenweider and of Lee and his associates, this lake can receive no more than on the order of 2,000 to 4,000 mt P/yr if oxygen is to be maintained in its hypolimnion under all conditions. For further discussion of this topic consult Lee et al. (14).

The OECD eutrophication modeling approach is also tuned; however, the tuning process is based on a statistical correlation involving load-response relationships for approximately 300 waterbodies in Western Europe, North America, Japan, and Australia. Because of the very large data base available in support of the OECD eutrophication modeling, it is the modeling approach of choice in predicting load-response relationships for waterbodies. Verification of the reliability of this approach has been accomplished in two ways. First, the original OECD load-response relationships, based on the 40 U.S. OECD waterbodies, have been found to be applicable to about 300 waterbodies located in the U.S., Canada, Western Europe, Japan, and Australia. Further, Rast et al. (17) have reviewed data on 9 waterbodies to which there has been a significant change in the P load and for which there was sufficient information on the characteristics before and after the P load change to apply the OECD eutrophication modeling approach. Their review has shown that these waterbodies track properly, i.e., parallel to the U.S. OECD line of best fit for the P load-planktonic algal chlorophyll relationship. The new chlorophyll level in these waterbodies would be reliably predicted based on the altered P load.

One of the most significant advantages of the OECD eutrophication modeling approach over the dynamic modeling approach is the marked difference in the amount of data needed to implement the two approaches. The OECD approach requires a minimal amount of data that can be readily obtained at a low cost. The dynamic modeling approach, because it must be tuned to each particular waterbody, requires a substantial data base; even after a seemingly sufficient data base is obtained it may be found that the model cannot be applied without undertaking a substantial additional research effort. Lee et al. (10) found this to be true in connection with applying the dynamic modeling approach to Lake Ray Hubbard near Dallas, Texas, where much more than simply adjusting the coefficients used in the model for the increased temperature was needed to make this approach fit. Even after a $300,000 15-month study of this waterbody, insufficient information was available to properly tune the model. One of the biggest difficulties in tuning dynamic models is their failure to properly model the exchange between water and sediments for nitrogen and/or phosphorus. Failure of these models to properly handle this exchange was another reason the dynamic model evaluated by Lee et al. (10) could not be fit to Lake Ray Hubbard.

DISCUSSION

It has been found through the OECD Eutrophication Study Program that the nutrient load-eutrophication response relationships originally developed by Vollenweider are a viable tool for establishing management programs for eutrophication-related water quality. While originally developed for lakes and impoundments, they have demonstrated applicability to the three reaches of the Potomac estuary. From a fundamental point of view, based on the nature of the relationships developed by Vollenweider, they should be equally applicable to all estuarine systems. The important parameters that must be evaluated for a particular estuary in the application of the OECD eutrophication model are the appropriate mean depth and hydraulic residence time. It is suggested that initially the approach developed by Jaworski of assuming a plug flow and morphological mean depth be tried. If chlorophyll concentrations measured during the summer and those predicted using these assumptions in the OECD eutrophication models are in reasonable agreement, then the simple assumptions for mean depth and hydraulic residence time would likely be appropriate for use with the system. If, however, there are major discrepancies between measured and predicted levels, then it would be necessary to modify the methods used to determine the mean depth and hydraulic residence time to consider the position and dynamics of the salt wedge. It is important in this tuning process to keep the influence of the salt wedge realistic in terms of expected hydrodynamic behavior. If assuming potentially reasonable mean depths and mixing between the salt wedge and the overlying water does not result in the chlorophyll falling within the population of data obtained in the U.S. OECD study, then this approach should not be used and further studies should be conducted to determine why this discrepancy exists. Until such time as sufficient experience has been gained in applying this approach to water quality management of estuarine systems, it will be necessary to check the validity of the load-response relationships for each particular estuary by comparing the predicted and measured chlorophyll concentrations.

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REFERENCES

1. Chapra, S., NOAA, Ann Arbor, Michigan. Personal Communication to W. Rast, IJC, Washington, D.C. May, 1979.
2. Jaworski, N.A. 1977. Section VIII - Multiple-State Lakes and Special Topics Limnological Characteristics of the Potomac Estuary. *In* L.

Seyb and K. Randolph, North American Project-A Study of U.S. Water Bodies, EPA-600/3-77-086, U.S. EPA-Corvallis.

3. Jaworski, N.A. 1979. Sources of nutrients and the scale of eutrophication problems in estuaries. Proc. International Symposium on Effects of Nutrient Enrichment in Estuaries, Williamsburg, Va. May 1979.
4. Jaworski, N.A., L.J. Clark, and K.D. Feigner. 1971. A water resources - water supply study of the Potomac estuary. Technical Report 35. Chesapeake Technical Support Lab, Middle Atlantic Region, U.S. EPA, Annapolis, Md.
5. Jones, R.A., W. Rast, and G.F. Lee. 1979. Relationship between summer mean and maximum chlorophyll *a* concentrations in lakes. *Environ. Sci. & Technol.* 13:869-870.
6. Lee, G.F., and R.A. Jones. 1977. An approach for development of a eutrophication control program for the Emilia Romagna coastal waters of the Adriatic Sea. Occasional Paper No. 27, Environmental Engineering, Colorado State University, Fort Collins, Col.
7. Lee, G.F., and R.A. Jones. 1977. An assessment of the environmental significance of chemical contaminants present in dredged sediments dumped in the New York Bight. New York District Corps of Engineers, Contract No. DACW 51-77-C-0011, Ocassional Paper No. 28, Environmental Engineering, Colorado State University, Fort Collins, Col.
8. Lee, G.F., and R.A. Jones. 1979. Water quality characteristics of the U.S. waters of Lake Ontario during the IFYGL and modeling contaminant load-water quality response relationships in the nearshore waters of the Great Lakes. Report to National Oceanic and Atmospheric Adminstration Great Lakes Research Laboratory, Ann Arbor, Mich.
9. Lee, G.F., and R.A. Jones. 1979. (In press). Effect of eutrophication on fisheries. American Fisheries Society, Bethesda, Md.
10. Lee, G.F., M. Abdul-Rahman, and E. Meckel. 1978. A study of eutrophication, Lake Ray Hubbard, Dallas, Texas. Occasional Paper No. 15, Environmental Engineering, Colorado State University, Fort Collins, Col.
11. Lee, G.F., R.A. Jones, and W. Rast. 1980. Availability of phosphorus to phytoplankton and its implications for phosphorus management strategies, *In*: Phosphorus Management Strategies for Lakes, Ann Arbor Science, Ann Arbor, MI.
12. Lee, G.F., W. Rast, and R.A. Jones. 1977. Recent advances in assessing aquatic plant nutrient load-eutrophication response for lakes and impoundments. Occasional Paper No. 14, Environmental Engineering, Colorado State University, Fort Collins, Col.
13. Lee, G.F., W. Rast, and R.A. Jones. 1978. Eutrophication of waterbodies: insights for an age-old problem. *Environ. Sci. & Technol.* 12:900-908.
14. Lee, G.F., W. Rast, and R.A. Jones. 1979. Use of the OECD eutrophication modeling approach for assessing Great Lakes' water quality. Occasional Paper No. 42, Environmental Engineering,

Colorado State University, Fort Collins, Col. *In* G.F. Lee and R.A. Jones. 1979. Water quality characteristics of the U.S. waters of Lake Ontario during the IFYGL and modeling contaminant load-water quality response relationships in the nearshore waters of the Great Lakes. Report to National Oceanic and Atmospheric Administration Great Lakes Research Laboratory, Ann Arbor, Mich.

15. Paulson, G. 1976. Report on the fish kill off the New Jersey coast and its potential causes and consequences. State of New Jersey Department of Environmental Protection, Trenton, N.J.
16. Rast, W., and G.F. Lee. 1978. Summary analysis of the North American (US portion) OECD Eutrophication Project: Nutrient loading-lake response relationships and trophic state indices. EPA-600/3-78-008.
17. Rast, W., G.F. Lee, and R.A. Jones. 1981. Predictive capability of the U.S. OECD phosphorus loading eutrophication response models. (In press).
18. Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorus and eutrophication in the coastal marine environment. *Science* 171:1006-1013.
19. Salas, H.J., and R.V. Thomann. 1978. A steady-state phytoplankton model of Chesapeake Bay. *Jour. Water Poll. Control Fed.* 50:2752-2770.
20. Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. *Jour. New Engl. Water Works Assoc.* 61:109-127.
21. Seyb, L., and K. Randolph. 1977. North American Project-A Study of U.S. Water Bodies, EPA-600/3-77-086, U.S. EPA-Corvallis.
22. Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to nitrogen and phosphorus as factors in eutrophication. Technical Report DAS/CSI/68, OECD, Paris.
23. Vollenweider, R.A. 1975. Input-output models, with special reference to the phosphorus loading concept in limnology. *Schweiz. Z. Hydrol.* 37:53-84.
24. Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *Mem. Ist. Ital. Idrobiol.* 33:53-83.
25. Vollenweider, R.A. 1979. Das Nahrstoffbelastungs-konzept als Grundlage fur den externen Eingriff in den EutrophierungsporzeB stehender Gewasser und Talsperren, Symposium des Wahnbachtalsperrenver bandes Veroffentlichung der Vortrage, Z. F. Wasser - und Abwasser-Forschung, 12, Jahrgang Nr2/79.
26. Vollenweider, R.A. 1979. Canada Centre for Inland Waters, Burlington, Ontario. Personal Communication to G. Fred Lee, Environmental Engineering, Colorado State University, Fort Collins, Col.
27. U.S. EPA. 1971. Algal Assay Procedure Bottle Test. U.S. EPA-Corvallis, Ore.
28. U.S. EPA. 1974. Marine Algal Assay Procedure Bottle Test. U.S. EPA-Corvallis, Ore.